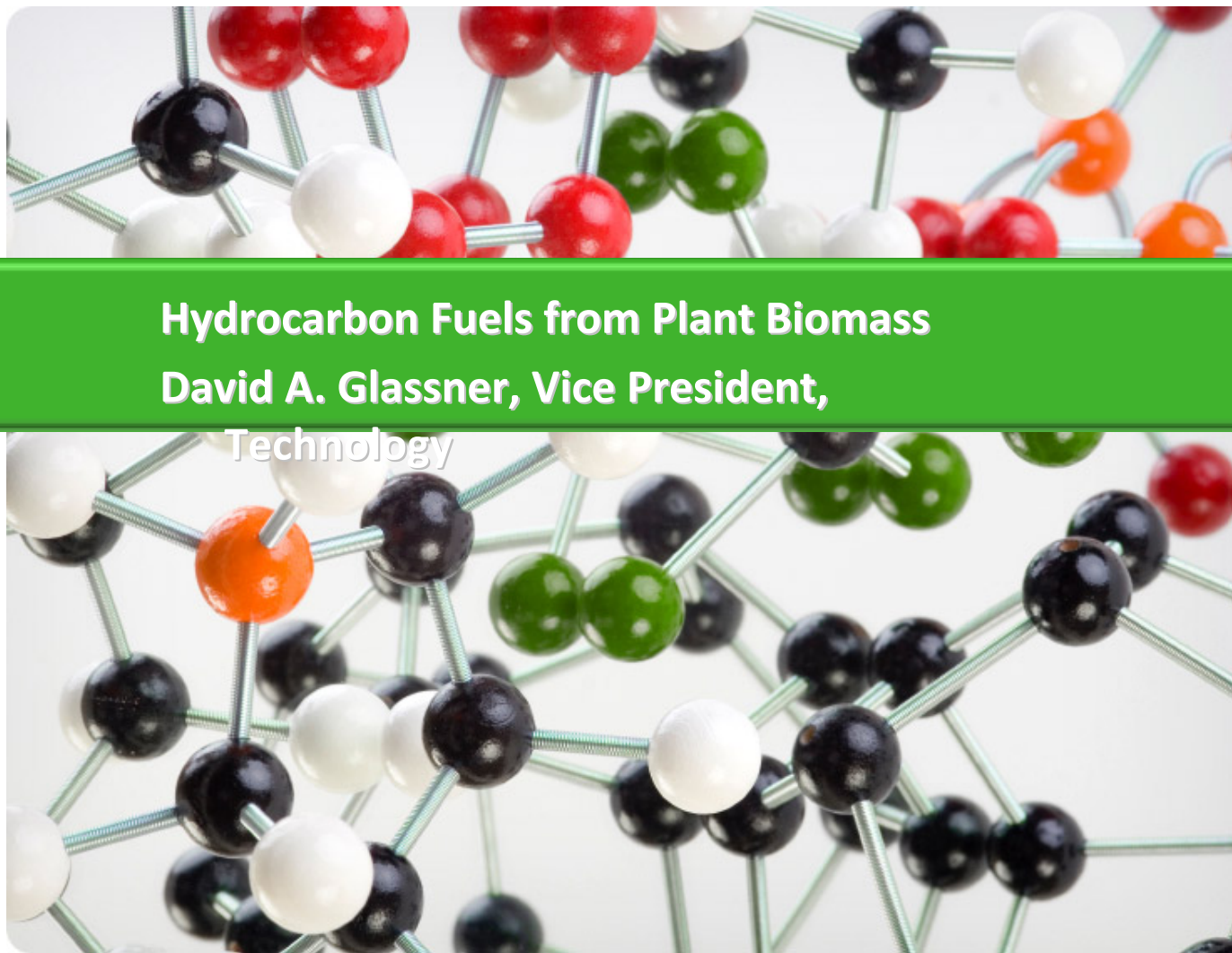




Advancing the New Era of Renewables

Hydrocarbon Fuels from Plant Biomass

David A. Glassner, Vice President,
Technology

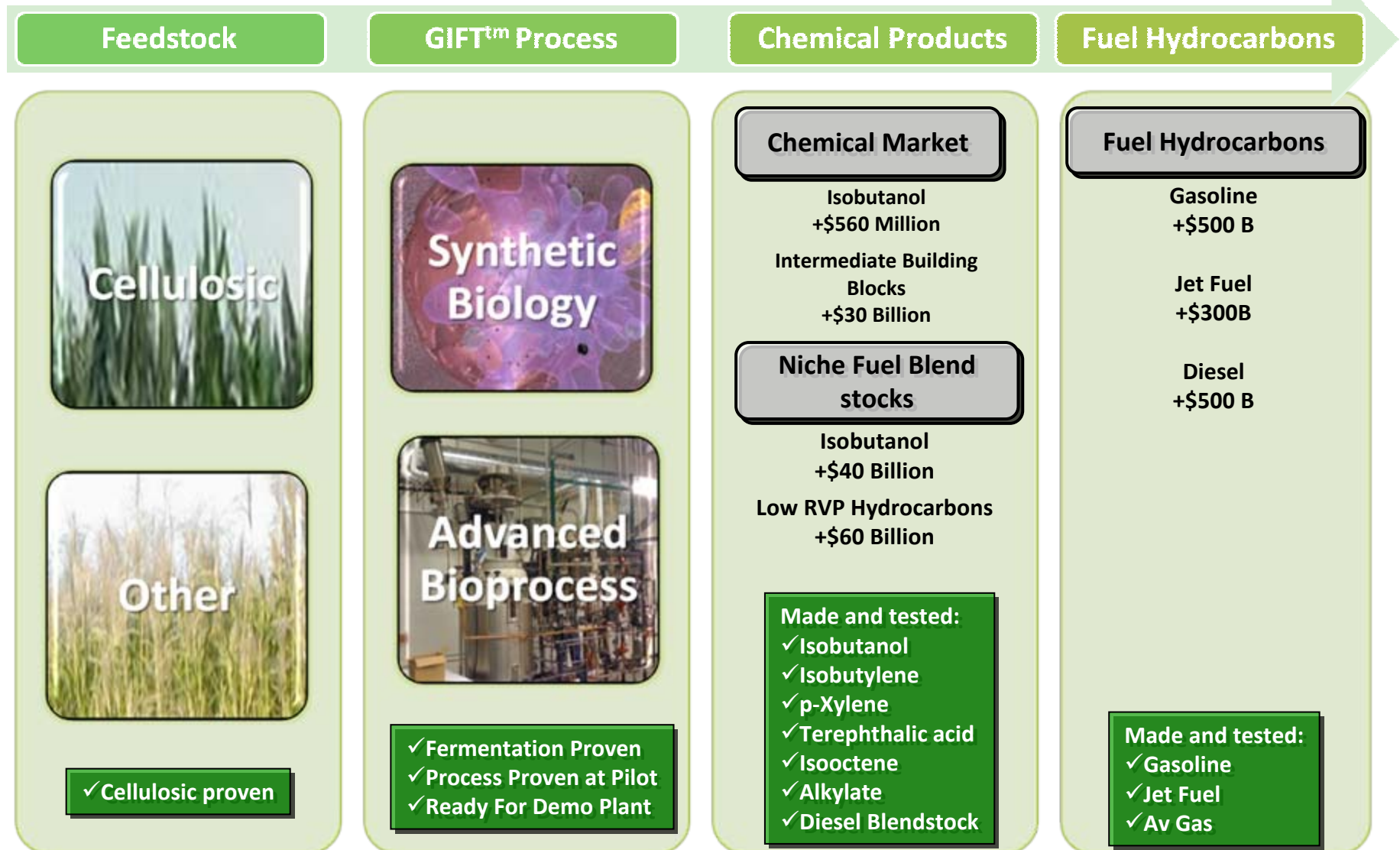


- Based in Denver, Colorado
- Venture funded by Khosla Ventures, Virgin Green Fund, Burrill & Company and Malaysian Life Science Fund
- ~50 people
- More than 100 patents & applications including exclusive licenses from UCLA and Cargill
- Pilot plant, laboratory & office space in Denver, Colorado totaling 30,000 square feet
- Exclusive development & commercialization agreements with ICM including retrofit & use of 1 million gallon per year pilot plant in St. Joseph, MO

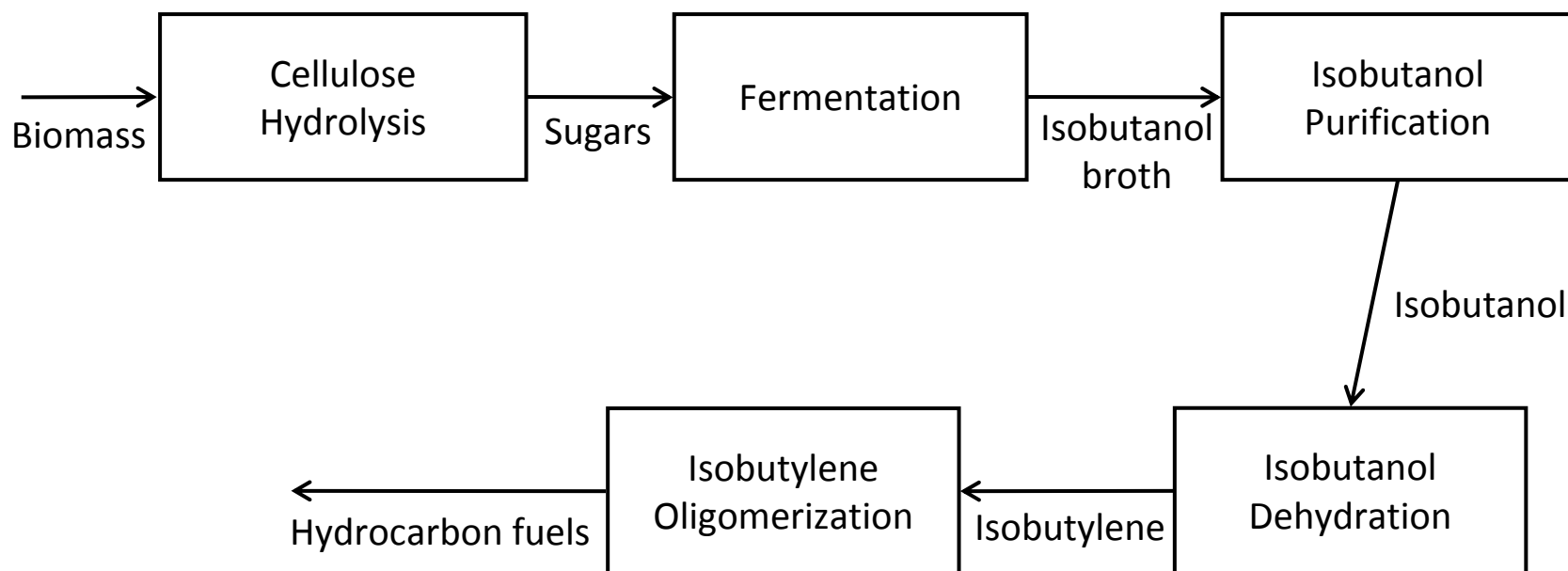
- Hydrocarbon fuels that solve refiner's challenges and provide environmental benefits can be made from plant biomass via the fermentation intermediate isobutanol
 - High yield isobutanol fermentation developed
 - Chemistry to convert isobutanol to a variety of hydrocarbon fuels molecules is simple and well known
 - Process technology for hydrocarbons is low energy input and reduces greenhouse gas emissions by 85%
 - Cash operating cost for hydrocarbon fuel is competitive with \$65 per barrel crude oil (without incentives)

Introduction to Hydrocarbons via Isobutanol From Cellulose

Hydrocarbons Can be Manufactured from Any Carbohydrate via Isobutanol Fermentation!



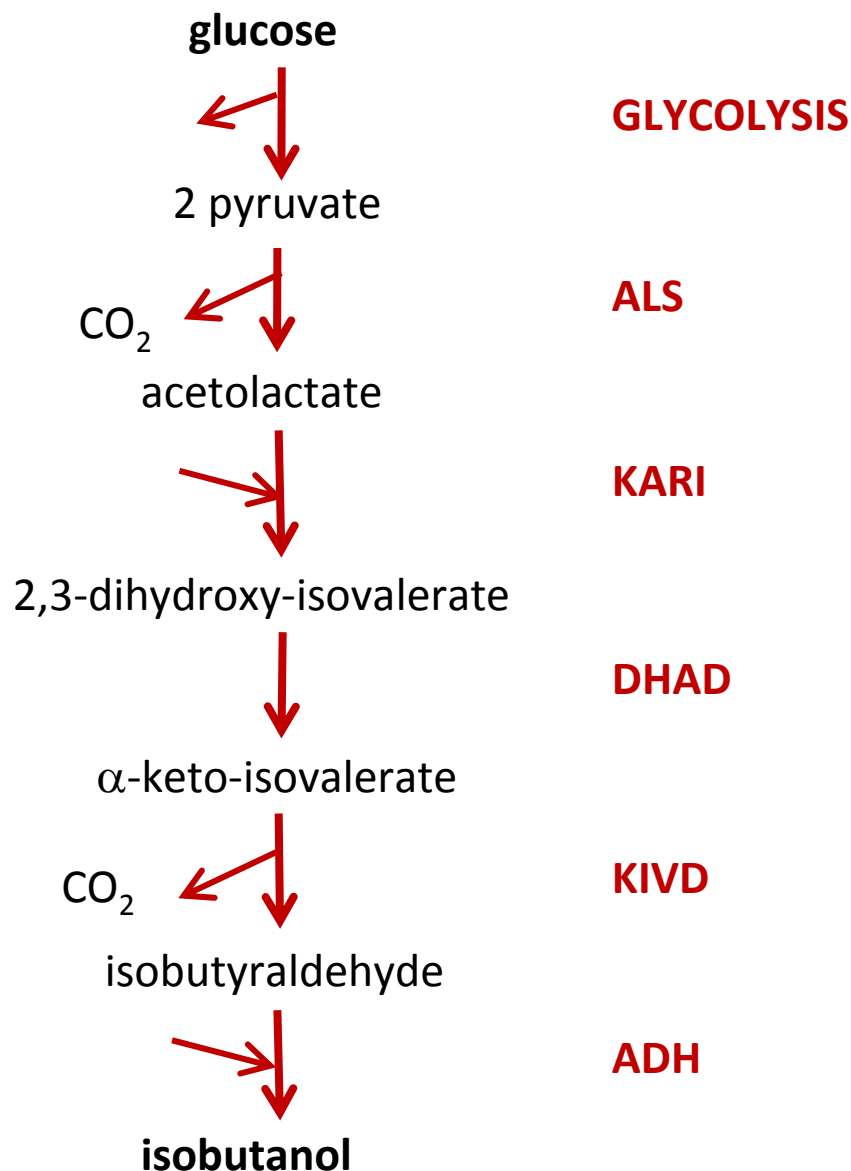
Hydrocarbons from Cellulose Process Schematic



- The 'new portion' of the process is the isobutanol fermentation and purification
- Many cellulose hydrolysis processes are being developed for commercialization
- Isobutanol dehydration to isobutylene is a simple process
- Isobutylene oligomerization is practiced in refineries today on a mixed olefin stream

Isobutanol Fermentation

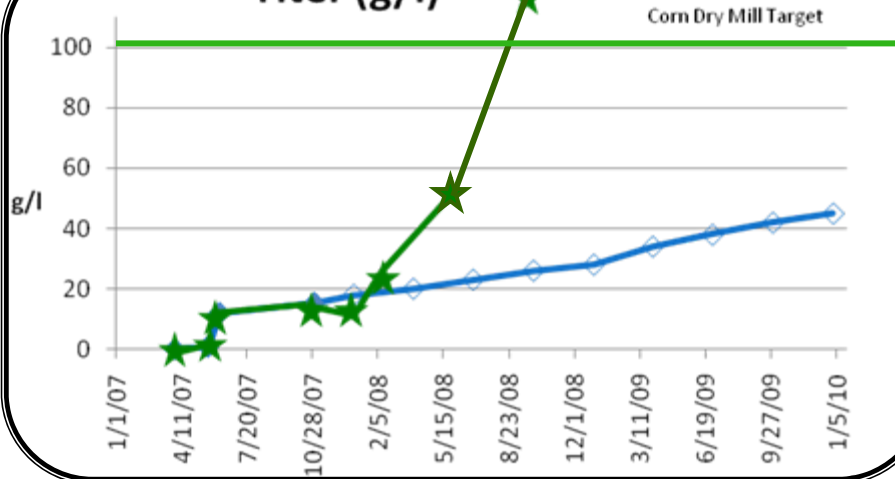
Gevo's Pathway Makes Only Isobutanol!



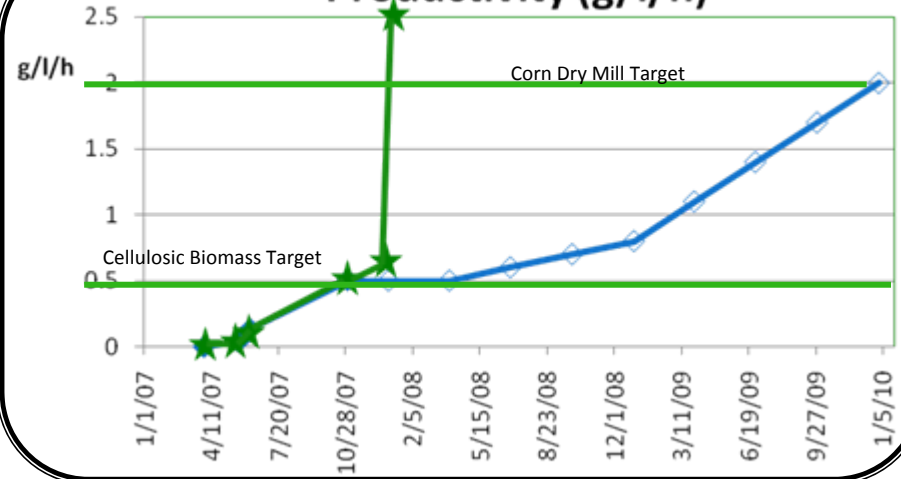
- One mole of glucose (MW 180) yields
 - 1 moles of isobutanol (MW 74 X 1 = 74)
 - 2 moles of carbon dioxide (MW 44 X 2 = 88)
 - 1 mole of water (MW 18 X 1 = 18)
- Theoretical isobutanol mass yield is 41.1%

Isobutanol Fermentation Meets Feasibility Targets!

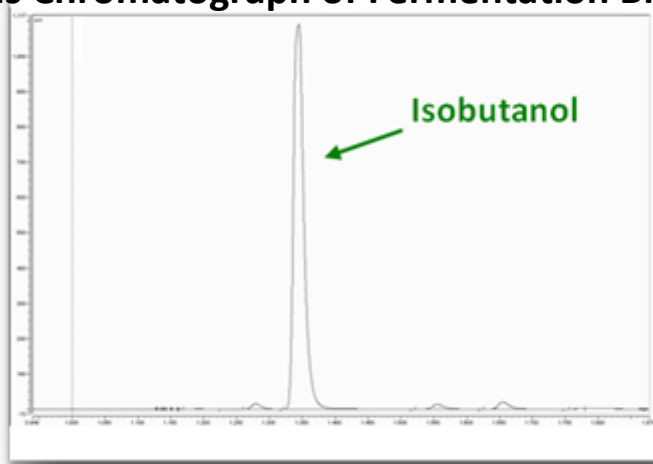
Titer (g/l)



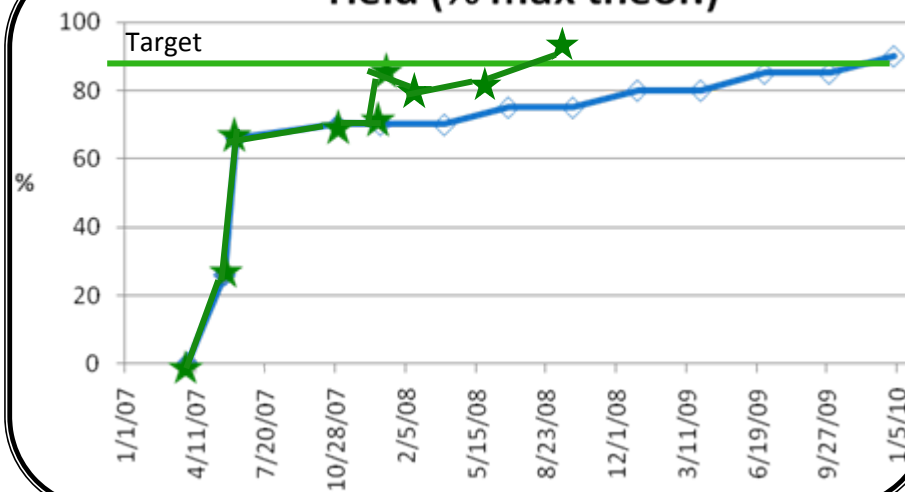
Productivity (g/l/h)



Gas Chromatograph of Fermentation Broth

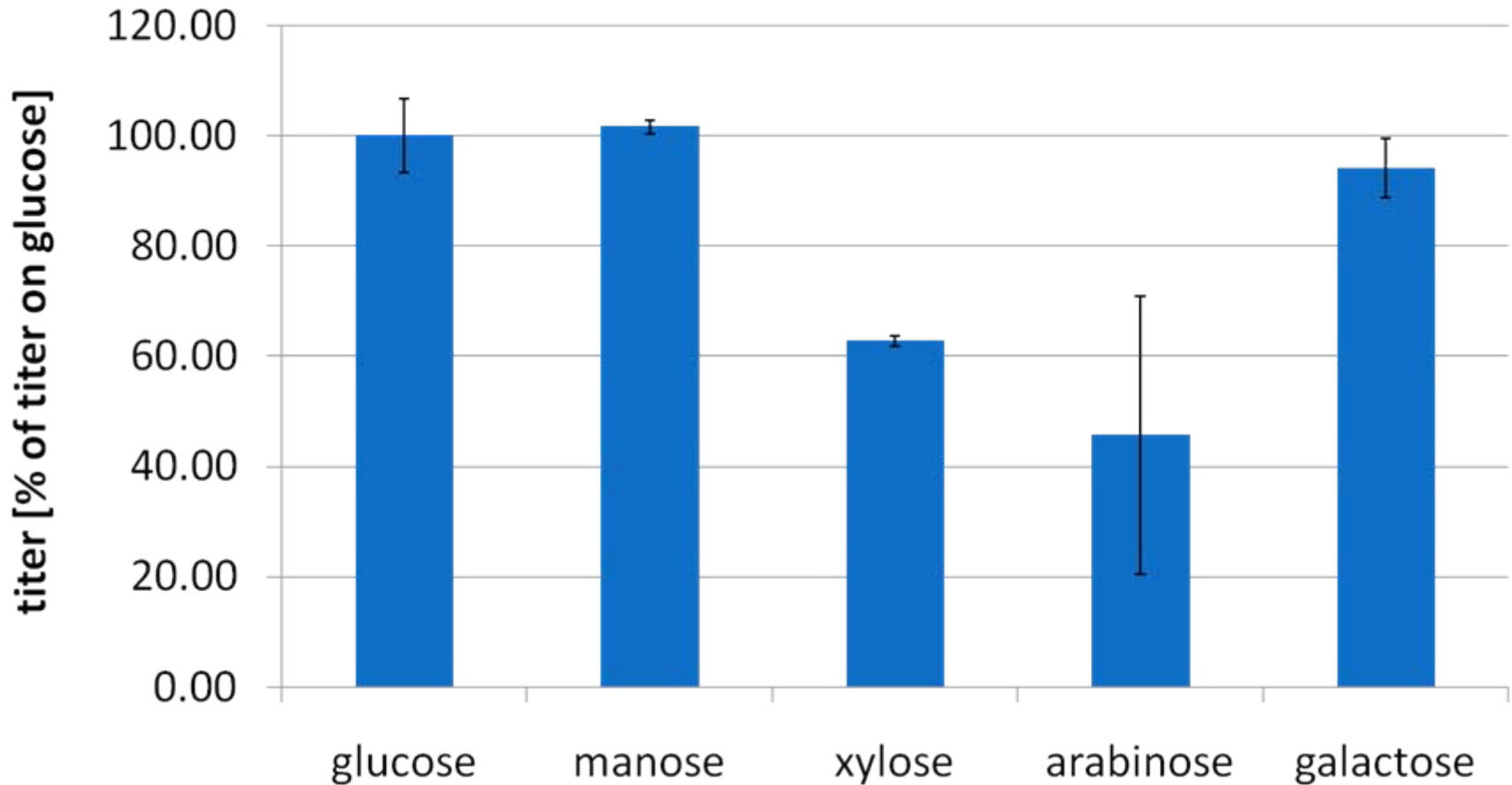


Yield (% max theor.)



Actual █
Plan █

Source: Gevo Testing



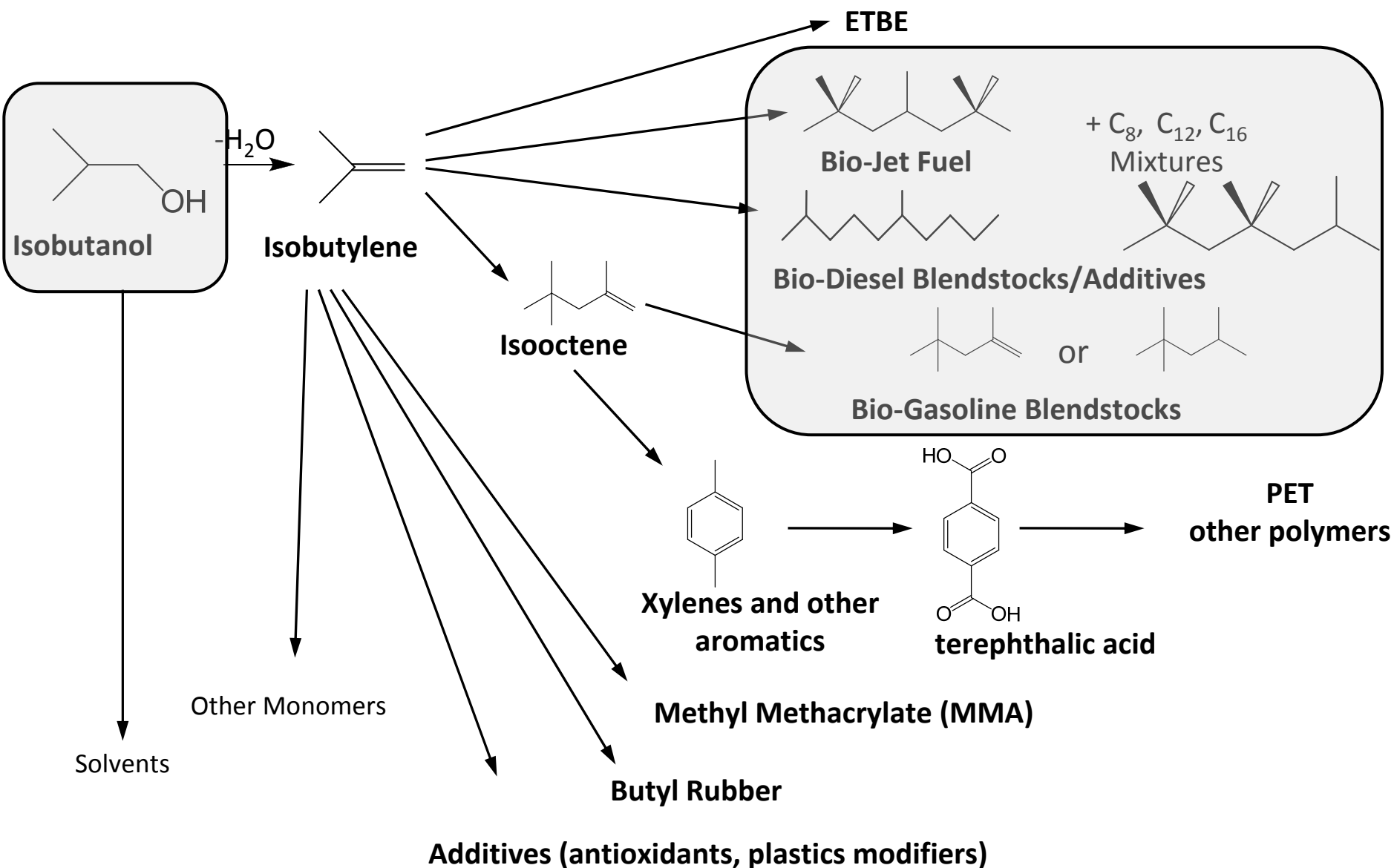
Isobutanol can be produced from a variety of lignocellulosic sugars

Low Cost Production Requires High Performance Fermentation!

	Ethanol	ABE	Isobutanol	Comments
Volumetric productivity (g/l/hr)	2.5	0.5	2.0	Fermentor volumes increased if glycolytic flux is not maintained
Mass yield (Theoretical)	0.48 0.51	0.34 0.40	0.39 0.41	High titer of sugar converted to ethanol and isobutanol keeps yield high
Final titer	130 g/l	28 g/l	105 g/l	High concentration keeps energy cost low
Microorganism	Yeast	<i>Clostridia</i>	Yeast	Yeast are proven in low cost industrial fermentors

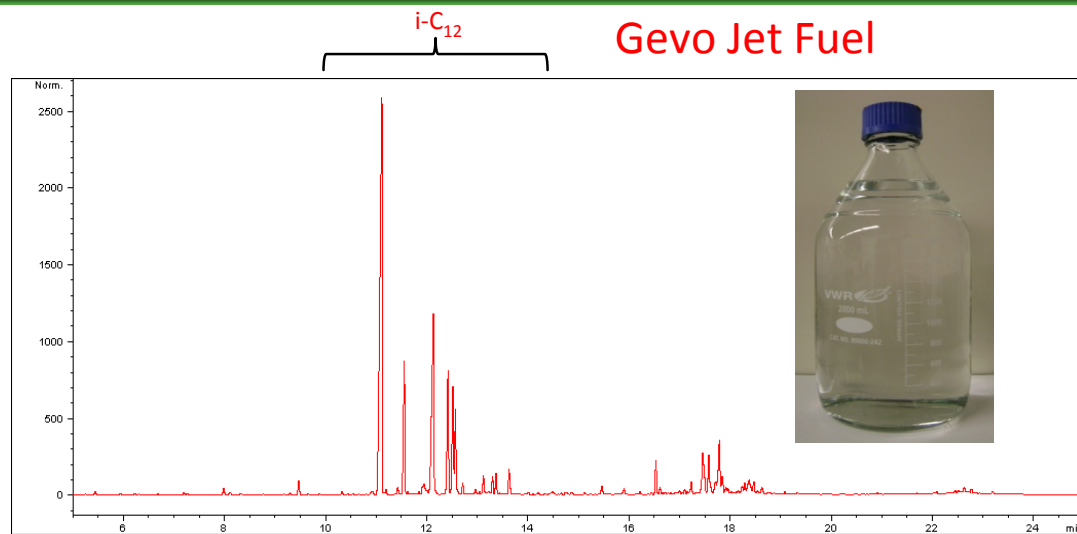
- All are batch fermentation data
- ABE data includes hydrogen production (Jones, Microbiological Review, 1986)

Hydrocarbon Fuels from Isobutanol

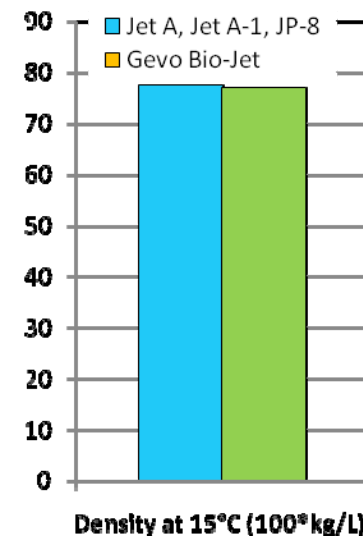
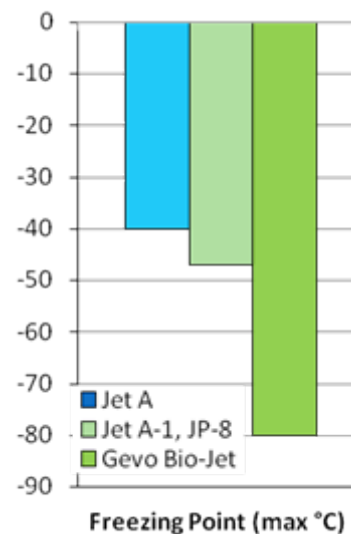
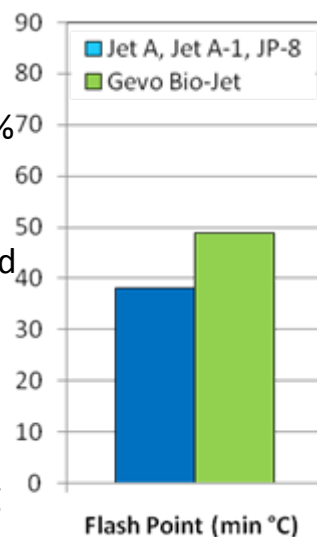


Jet Fuel Blendstock Meets ASTM Specifications!

- Value added:
 - Flash point is high
 - Freezing point is low
 - Flexibility to blend
- Unique composition is patentable
- First Sasol Synthetic Jet was C12-centered isoparaffin mixture with similar properties
- As is meets *all* ASTM specifications except volumetric density (0.768 kg/L vs. 0.775 kg/L)
 - Blending with 25% Jet A or with 10% Gevo aromatics meets all ASTM specifications
 - D1655 specification may be changed to lower density
 - T50-T10 meets proposed synthetic jet fuel requirements
- Meets energy density (43.2 MJ/kg vs. 42.8 MJ/kg)



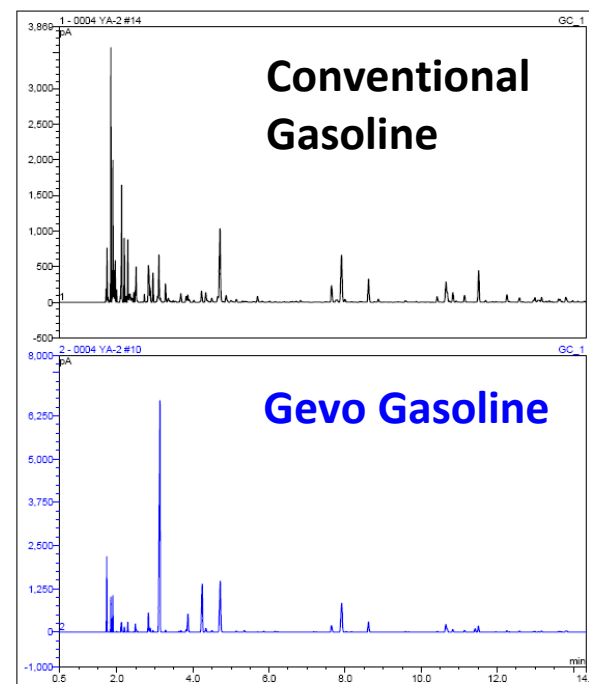
GC-FID Agilent 7890A, DB-5 column, temperature program started at 40 °C heated up at 10 °C/min to 240 °C



Gasoline is composed of three major components:

- High RVP material to provide ignitable vapor to engine
 - pentanes, butanes, light olefins from some refineries
- Low RVP, high octane, high energy aliphatic material for energy content and performance
 - C6-C10 isoparaffins, primarily isooctenes/isooctanes
- Low RVP, high octane, high energy aromatic material for energy content and performance
 - BTX (benzene, toluene, xylenes) from reformer
 - Higher levels of aromatics are in premium blends

	Density (g/L)	RVP (psi)	Octane Number [(R+M)/2]
Gevo Butanes	580	54	92
Gevo Isooctanes	700	2	98-100
Gevo Olefins	716	1.8	103
Gevo Aromatics	870	2-3	99
Gevo Isobutanol	802	4-5	98-102
Gevo Gasoline Blend	740	7	99



Challenge is to convert branched olefin to unbranched oligomers with high cetane:

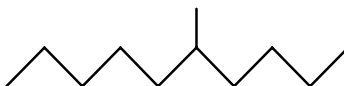
- Even unbranched olefins usually oligomerize to isoparaffins
- Linear paraffins are produced commercially with expensive oligomerization of ethylene
- High temperatures favor unbranched material but cracking occurs

Key strategy for generating linear paraffins:

- Use shape-selective catalysts to prevent branched material from forming
- Inactivate surface of catalyst so that only shape-selective portion reacts
- Run reaction at highest temperature possible without cracking

Results:

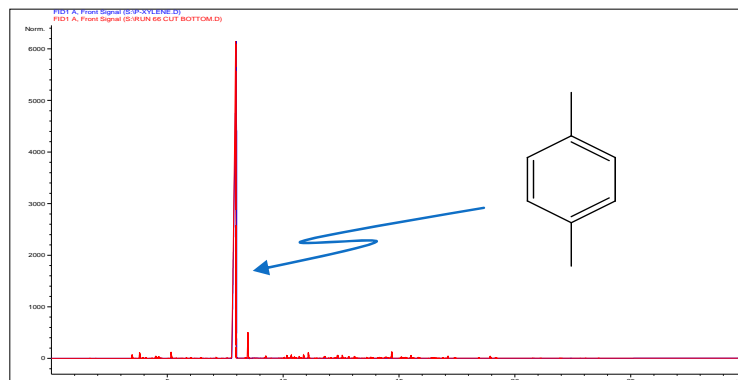
- Conditions - collidine treated ZSM-5 zeolite at 220°C and 1300 psi
- Monomethylparaffin fraction produced in >20% yield (20 g product/90 g isobutylene)
- Monomethylparaffins meet ASTM specs for No. 1 Diesel including cetane number >68



Gevo Diesel has cetane # >50

p-Xylene and Terephthalic Acid from Isooctene:

- Optimized in lab to prepare for production from Gevo isobutanol
- p-xylene from isooctene: >95% selectivity, highest single pass conversion in literature
- terephthalic acid from p-xylene: high yield and clean product



BTEX (Benzene, Toluene, Ethyl benzene, Xylenes):

- Produced from isobutylene using typical refinery reforming conditions
- Primary product is benzene and toluene, by-products are hydrogen and cracked HCs

Heavy Aromatics (t-Butyl Benzenes) for Jet Fuel:

- Alkylation of benzene and toluene with isobutylene
- Alkylated benzenes have high flash point, burn cleaner than naphthalenes

Technology Summary

	Ethanol	Isobutanol	Isooctene
Energy content of fuel (BTUs/gallon)	76,000	95,000	112,000
Fuel density (g/ml)	0.7894	0.8106	0.733 ¹
Energy content of fuel (BTUs/pound)	11,600	14,100	17,500
Mass fraction fuel yield (pounds fuel per pound sugar)	0.48	0.39	0.30
Energy produced (BTUs fuel per pound sugar converted)	5,500	5,500	5,400

¹ 85% isooctenes and 15% C12s

	Ethanol	Isobutanol
BTUs energy per gallon fuel recovered	14,000	15,000
BTUs energy per BTU fuel recovered	0.18	0.16

Hydrocarbons from Cellulose Reduce Greenhouse Gas Emissions by 85% Compared to Gasoline



	Isooctene	Gasoline
Greenhouse gas emissions (carbon dioxide equivalent grams per million BTU of fuel) Based on Wang et. Al., 2007	15,000 ^{1,2}	98,000 ¹

¹ Greenhouse gas emissions from Wang et. al., 2007

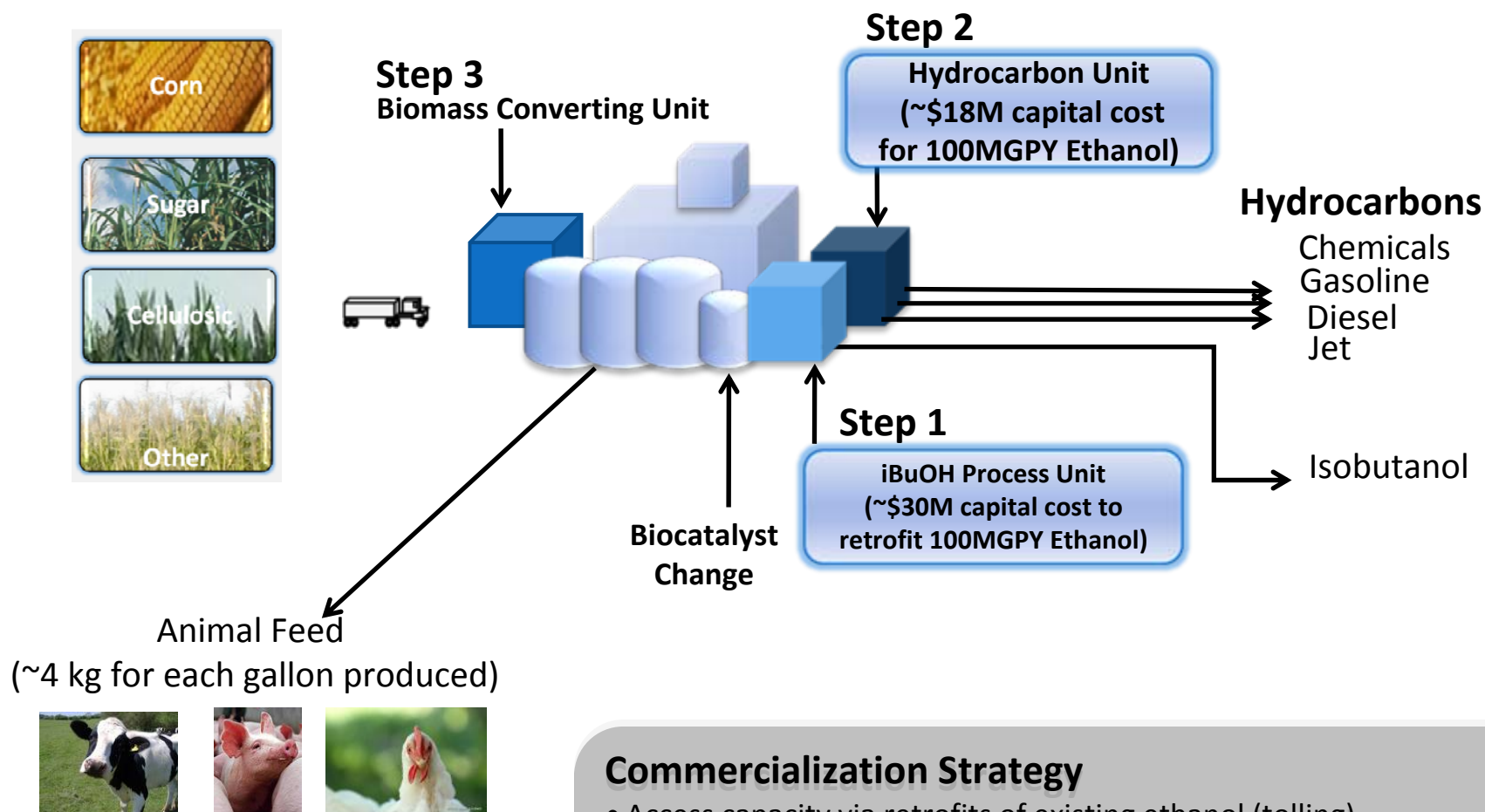
² Cellulosic conversion process using switchgrass, dilute acid prehydrolysis and cellulase enzyme hydrolysis.

	Ethanol	Isobutanol	Isooctene Rich ¹
Cash operating cost (\$/gallon)	1.18	1.44	1.86
Gallons fuel for 1 million BTUs fuel	13.2	10.5	9.4
Cash operating cost (\$/million BTUs fuel)	15.53	15.16	16.62

- At \$65/barrel crude wholesale gasoline is about \$1.80 per gallon
- Cash operating cost for \$50/ton biomass or \$3/bushel corn
- Isooctene rich fraction is a premium gasoline blend stock with 1.8 RVP and 96 octane (15-40 cents per gallon premium to wholesale gasoline)
- Helps refiners meet low vapor pressure gasoline regulations to reduce ozone and VOCs

Pathway to Commercialization

Capital Light Approach: Re-purpose Ethanol Plants



Commercialization Strategy

- Access capacity via retrofits of existing ethanol (tolling)
- Enter market with high value fuel products
- Use existing petrochemical channels and infrastructure
- Add technology and production capability incrementally
- Readily scalable technology

- Hydrocarbon fuels that solve refiner's challenges and provide environmental benefits can be made from plant biomass via the fermentation intermediate isobutanol
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